The top quark (EW) couplings at future colliders

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The top quark and the Higgs factory

Everyone (including European strategy ‘13+’20):

“the highest-priority next collider is an e^+e^- Higgs factory”

* fill in your favourite project here

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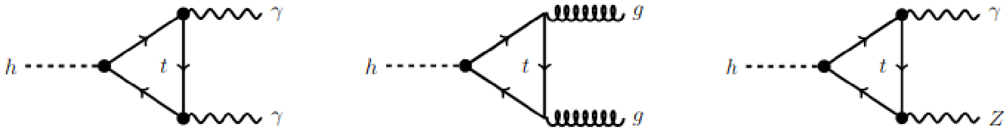
The top quark

This idea of a"Higgs factory" is an (over)simplification; any future e^+e^- collider is much more than that; the promise of the top quark tends to be forgotten in our (understandable) excitement about the Higgs boson

The EW sector was scrutinized precisely by LEP/SLC, but the top quark escaped scrutiny at the previous generation of e^+e^- colliders

Close connections to the Higgs sector: the top quark has O(1) Yukawa coupling and rules the loop diagrams ($gg \rightarrow H$, $H \rightarrow \gamma\gamma$)



Top is very present in many extensions of the Standard Model

The top quark at future e$^+$e$^-$ colliders

Today

Top might bring a surprise

Richard, arXiv:1403.2893
Durieux et al., arXiv:1807.10273
CLIC, arXiv:1812.02093
LCC physics WG, arXiv:1908.11299

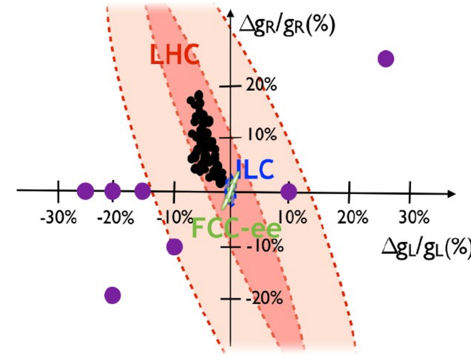
The interplay of top and Higgs in EFT fits

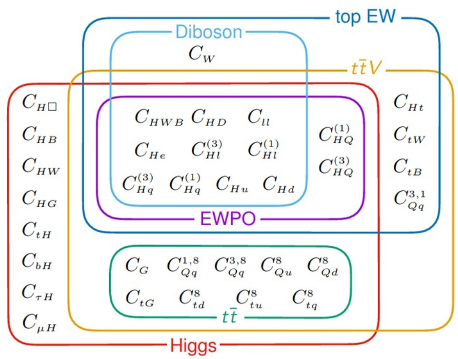
Durieux et al., arXiv:1809.03520
S. Jung et al., arXiv:2006.14631
Ellis et al., arXiv:2012.02799

Top mass is key for SM consistency

Baak et al., arXiv:1407.3792
Degrassi et al., arXiv:1205.6497
HL-LHC, arXiv:1902.04070
CLIC, arXiv:1807.02441

In backup material





t $I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}$ e Top = +1

HTTP://PDG.LBL.GOV Page 1 Created: 6/1/2020 08:28

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Mass (direct measurements) $m = 172.76 \pm 0.30$ GeV [a,b] (S = 1.2)
Mass (from cross-section measurements) $m = 162.5^{+2.1}_{-1.5}$ GeV [a]
Mass (Pole from cross-section measurements) $m = 172.4 \pm 0.7$ GeV
$m_t - m_{\bar{t}} = -0.16 \pm 0.19$ GeV
Full width $\Gamma = 1.42^{+0.19}_{-0.15}$ GeV (S = 1.4)
$\Gamma(Wb)/\Gamma(Wq(q = b, s, d)) = 0.957 \pm 0.034$ (S = 1.5)

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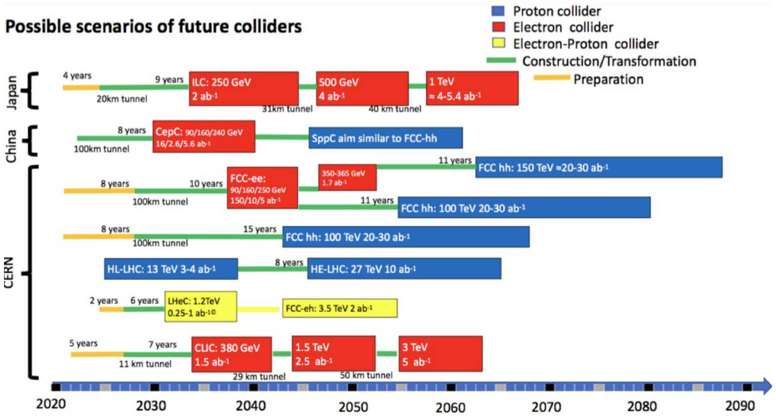
Prospects for future collider projects



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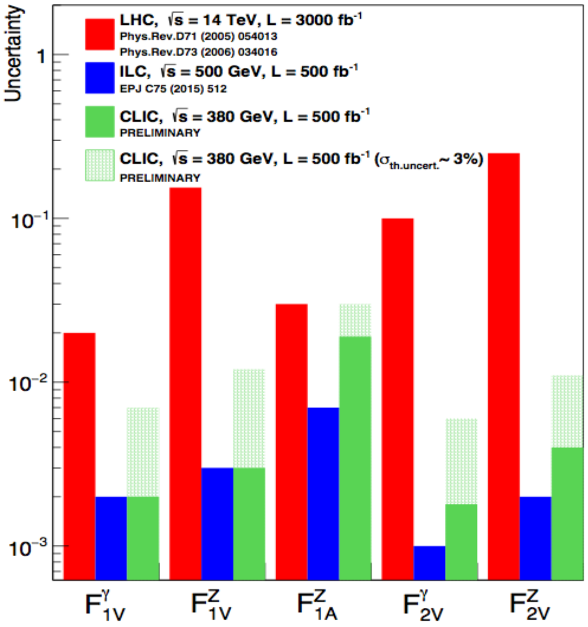
Top quark couplings



Can we predict the potential of a collider?

Data makes us smarter!

Famous examples:

- LEP/SLC vertex detectors enabled “unforeseen” measurements
- LHC top physics as opposed to gloomy prospects of hep-ph/0204087*

* **4.4 Top-quark physics**

Given the large top quark cross-section, most of the top physics programme should be completed during the first few years of LHC operation [32]. In particular, the $t\bar{t}$ and the single-top production cross-sections should be measured more precisely than the expected theoretical uncertainties, and the determination of the top mass should reach an uncertainty (dominated by systematics) of $\sim$ 1 GeV, beyond which more data offer no obvious improvement.

We must bank on “unpredictables”: theory progress, the battle against systematics

The S2 scenario for Higgs (and top) represent “targets” that attempt to predict this progress

Systematic uncertainties?

Extreme example: ATLAS inclusive $t\bar{t}$ cross section in lepton+jets final state, 139/fb at 13 TeV, PLB 810 (2020) 135797

Statistical uncertainty : 0.05%
Systematic uncertainty : 4.3%

Systematic can be reduced with work:
Background → move to di-lepton channel
Detector → in-situ calib./di-lepton
MC modell → improve MC (NNLO, tunes)
Luminosity → target is 1%

Progress will continue; 1/sqrt(L) is hard to keep up with; HL-LHC uncertainty of 1% seems on the edge of doable.

Category	$\frac{\Delta\sigma_{\rm fid}}{\sigma_{\rm fid}}$ [%]	$\frac{\Delta\sigma_{\rm inc}}{\sigma_{\rm inc}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_T NNLO reweighting	±0.4	±1.1
$t\bar{t}$ $h_{\rm damp}$	±1.5	±1.4
$t\bar{t}$ PDF	±1.4	±1.5
Background modelling		
MC background modelling	±1.8	±2.0
Multijet background	±0.8	±0.6
Detector modelling		
Jet reconstruction	±2.5	±2.6
Luminosity	±1.7	±1.7
Flavour tagging	±1.2	±1.3
$E_T^{\rm miss}$ + pile-up	±0.3	±0.3
Muon reconstruction	±0.6	±0.5
Electron reconstruction	±0.7	±0.6
Simulation stat. uncertainty	±0.6	±0.7
Total systematic uncertainty	±4.3	±4.6
Data statistical uncertainty	±0.05	±0.05

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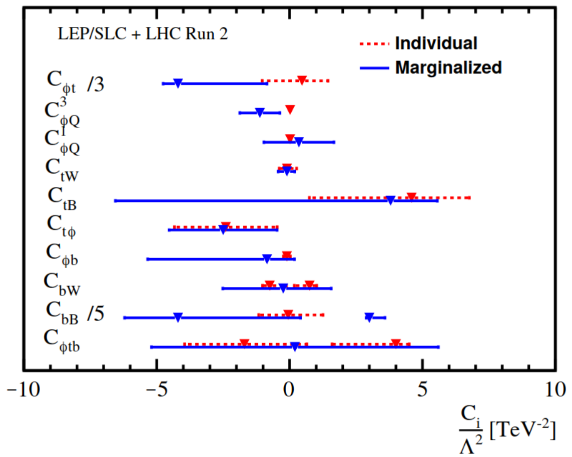
Progress at the LHC?



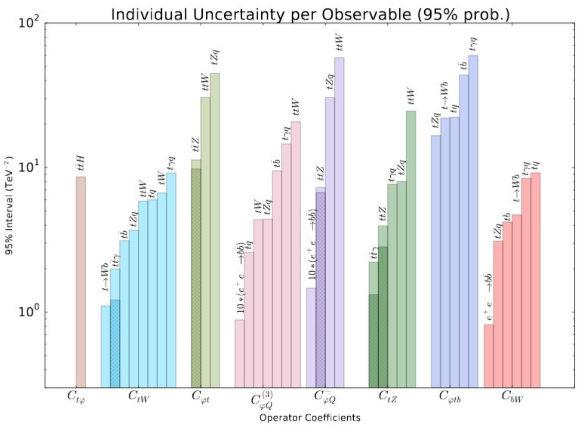
First iteration in 2018/9: "early run 2" (36/fb)

Durieux et al., arXiv:1907.10619

EFT fit to top quark EW couplings

Second iteration in 2020/1: "rull run 2" (140/fb)

Moreno et al., to be published (soon)



Many measurements indeed limited by systematics

"more data offer no obvious improvement"

Even stat. uncertainties fall short of 1/sqrt(L) progress

"picky selection of di-lepton events helps reduce syst."

Differential x-sec for ttγ (and ttZ) take advantage of E-growing sensitivity

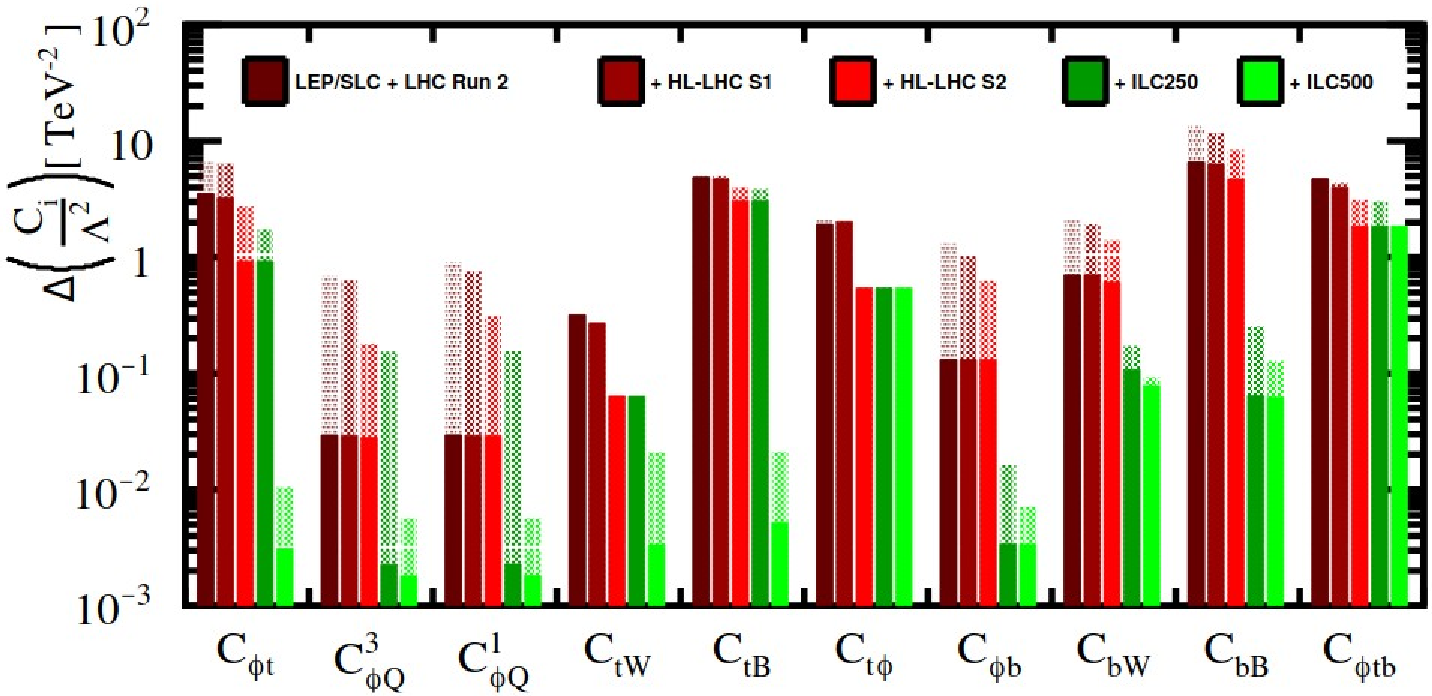
Bounds improve by a factor 1.5-1.8 for most coefficients: not quite 1/sqrt(L), but close

Bounds become much more robust – less dependence on quadratic terms

Electro-weak couplings of the top quark

A long history of studies show that an e^+e^- collider above the $t\bar{t}$ threshold is the best laboratory to study the **$\gamma t\bar{t}$ and $Zt\bar{t}$ vertices**, *arXiv:1307.8102, arXiv:1505.0620, arXiv:1503.01325, 1509.09056, arXiv:1503.04247*

Improve current bounds and the most optimistic HL-LHC by orders of magnitude

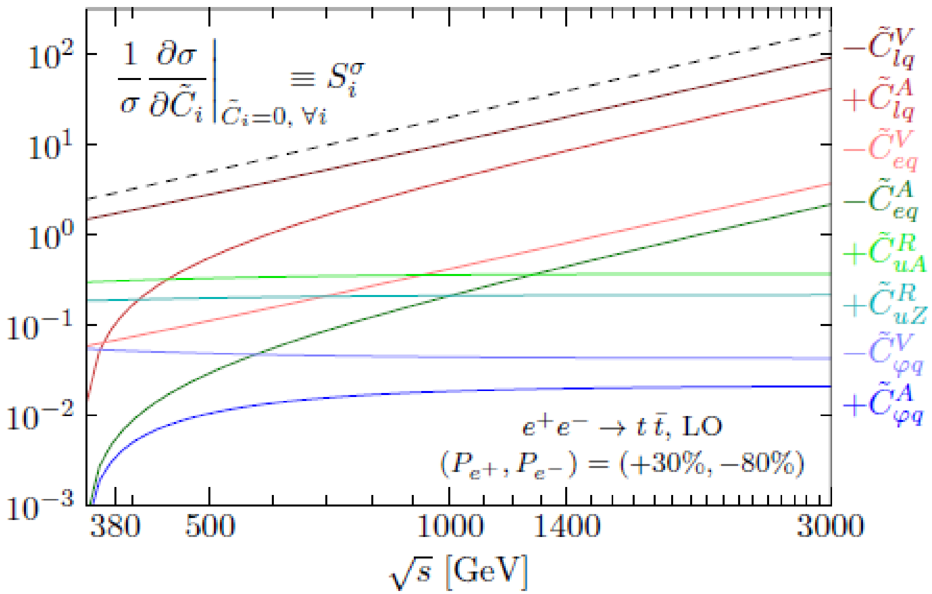


Modern EFT interpretation, comparison with HL-LHC, arXiv:1907.10619

The optimal e+e- program

An optimal top physics program must cover two energies above the tt threshold

Total cross section (left pol.):



Energy & precision

Getting close to the New Physics pays off; impact grows with energy

Effect of two-fermion operators best probed at ~400-500 GeV

Effect of four-fermion operators felt most strongly at high energy

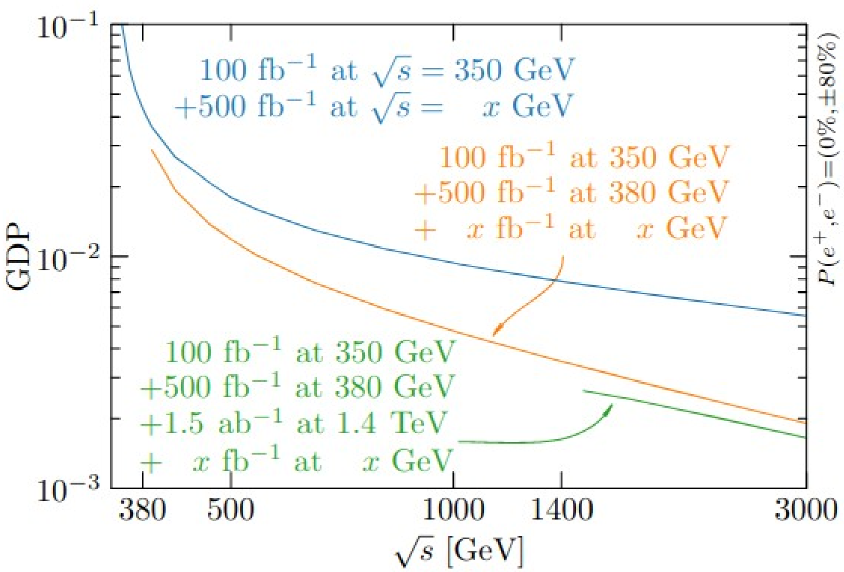
Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

CLIC New Physics paper, arXiv:1812.02093

The optimal e^+e^- program (bonus slide added a posteriori)

An optimal top physics program must cover two energies above the tt threshold



Energy & precision

Running at two energies above the tt threshold, we disentangle contributions by 2- and 4-fermion operators

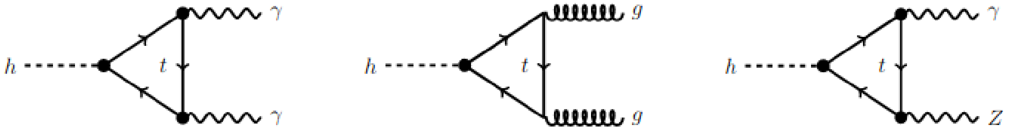
The bounds (quantified with GDP – the hypervolume of allowed parameter space) decrease rapidly as the lever arm of the second energy point increases

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

CLIC New Physics paper, arXiv:1812.02093

Top and Higgs



The top quark Yukawa coupling

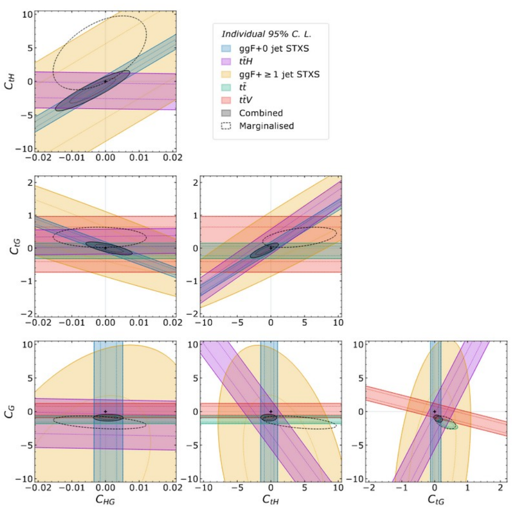
The 250 GeV run offers excellent “indirect” sensitivity to the top quark Yukawa coupling

$\Delta y/y < 1\%$ from $H \rightarrow gg$	*Mitov et al., arXiv:1805.12027*
$\Delta y/y < 1\%$ from $H \rightarrow \gamma\gamma$	*Jung et al.,arXiv:2006.14631*

Assuming the SM for other couplings

A “direct” measurement in ttH requires sqrt(s) > 550 GeV

robust determination to <3% precision in global analysis	*Price et al., arXiv:1409.7157*
unambiguous identification of any deviation from the SM	*Jung et al.,arXiv:2006.14631*
optimal energy remains to be identified in rigorous study	*LCCphysWG, arXiv:1908.11299*



Global Higgs/EW/top fit to LHC data by Ellis et al. finds several operators - C_{tH} ,C_{tG}, C_{HG} - are entangled. This prevents a robust determination of the top Yukawa coupling from the $gg \rightarrow H$ and $H \rightarrow \gamma\gamma$ measurements. The marginalized limit is 5x the individual limit, and is dominated by ttH.

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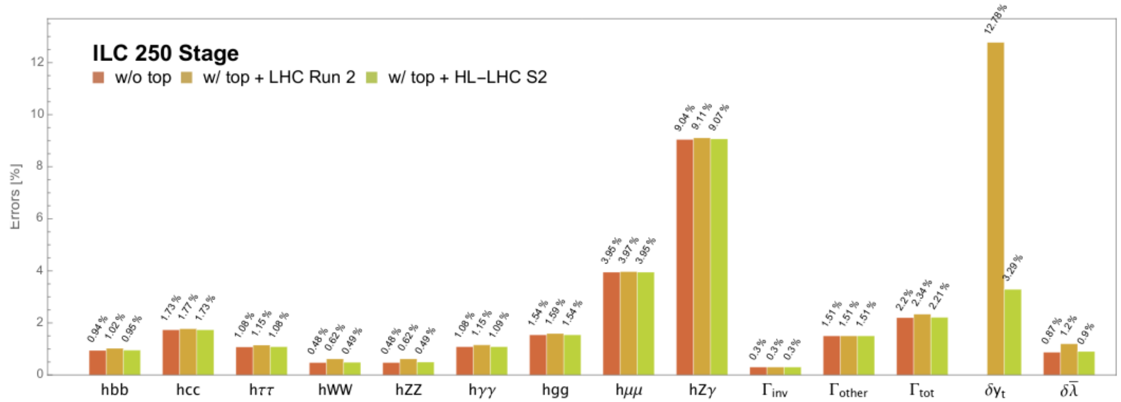
Grand, global SM EFT fits

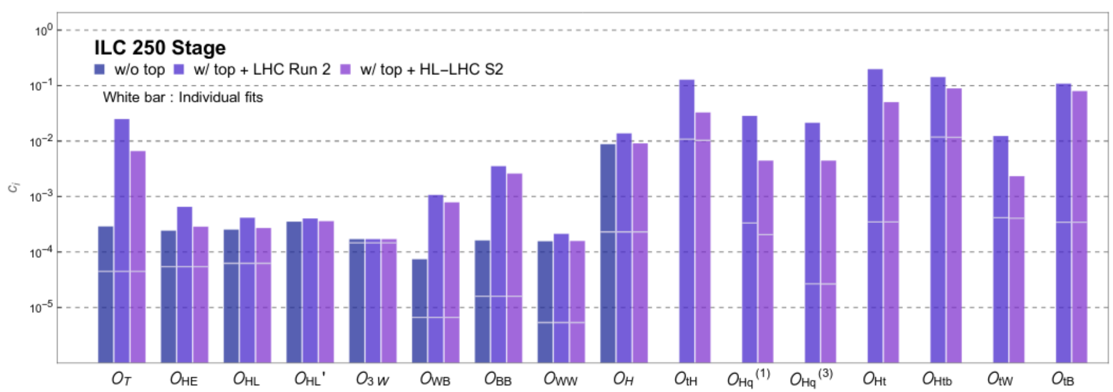
S. Jung. J. Lee, M. Perelló, J. Tian, M.V., arXiv:2006.14631

Top and bottom EW couplings affect 250 GeV Higgs fit considerably

Physical Higgs couplings largely shielded from extra degrees of freedom



Limits on Wilson coefficients are affected by inclusion of top operators, even with the most optimistic HL-LHC prospects



[See also S. Jung]

Summary

Top couplings at future facilities

The LHC program progresses; only slightly behind the most aggressive scenario

- Ultimate reach of HL-LHC remains a challenge – monitor progress closely
- Control of systematics bodes well for FCChh and SPPC prospects

The interplay of H and t operators requires tight bounds on the latter (beyond HL-LHC-S2)

- <1% indirect measurement of y_t at 250 GeV e+e- (under SM assumptions).
- A direct measurement of y_t requires 550 GeV or more

Runs above threshold and at very high-energy e+e- collisions needed for lltt operators.

The optimal program of future facilities remains to be formulated; global EFT fits (as in Ellis, Madigan, Mimasu, Sanz, You) are a valuable tool here; I expect we need e+e- run(s) above tt threshold to fully characterize the SM

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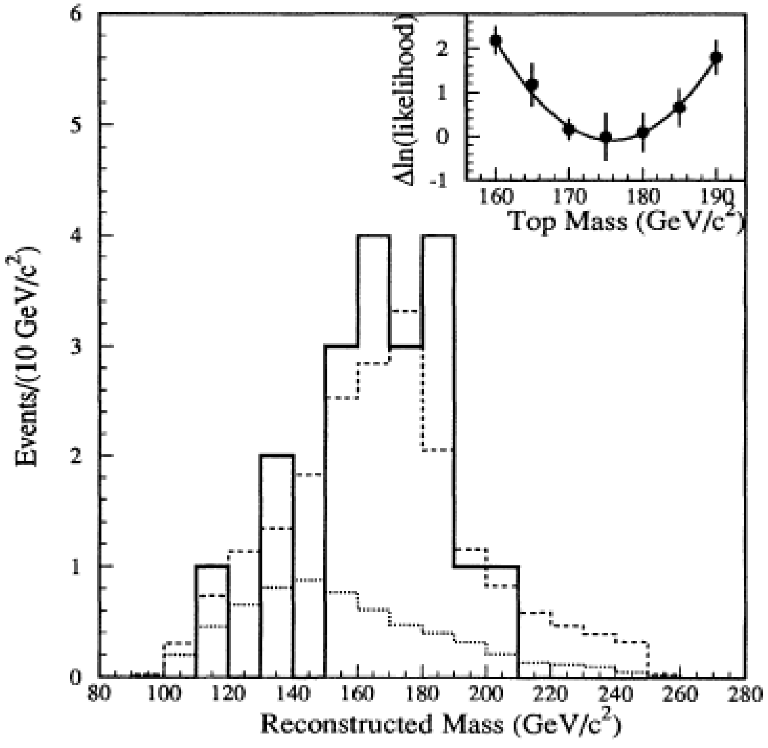
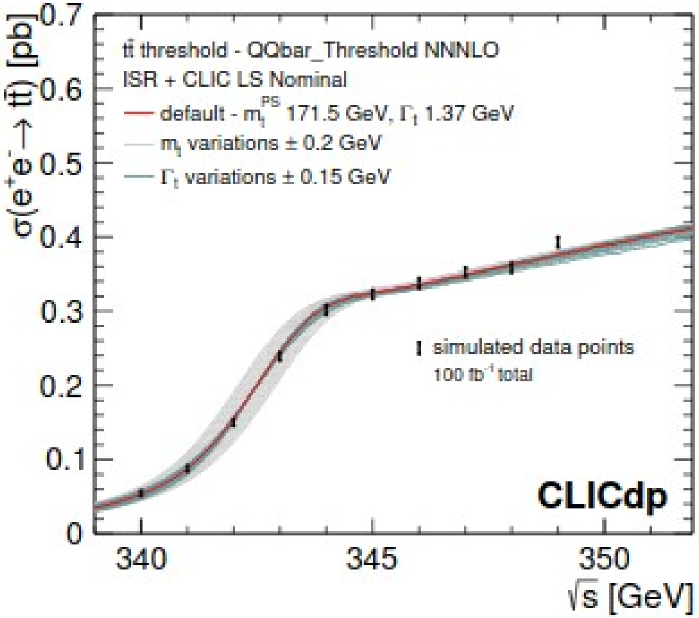
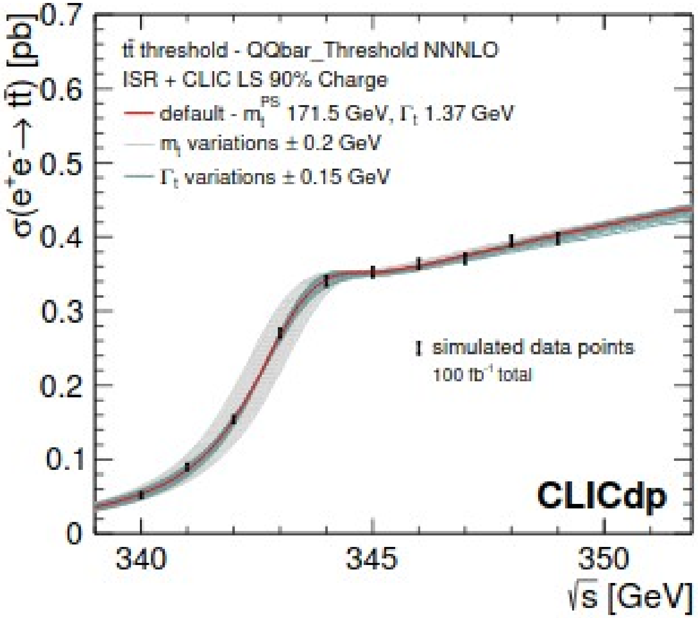
Top quark mass



Top quark mass from threshold

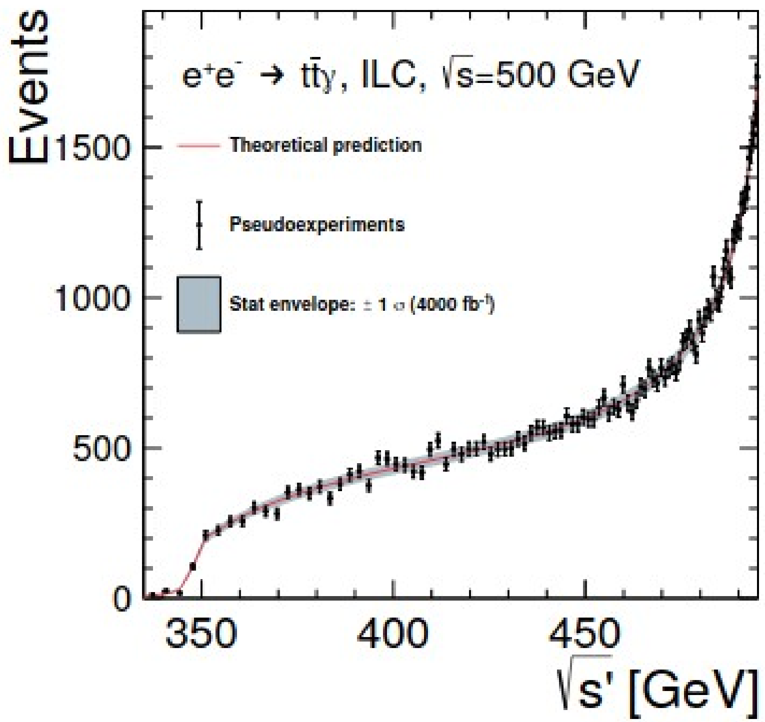
Idea goes back to 1980s (Gusken et al. ‘85, Fadin & Khoze ‘87, Strassler & Peskin ‘91)
Theory exists to N^3LO (Beneke et al. ‘16) and NNLO+NNLL (Hoang ‘14) precision
Prospects studies (Martinez ‘03, Horiguchi et al., ‘13, Seidel ‘13, CLIC ‘, Zarnecki ‘21)
Threshold line shape depends on m_t, Γ_t, y_t, α_s. A goldmine! Hard to extract all 4!
All machines ~ equivalent once lumi. spectrum is corrected (Poss, arXiv:1309.0372)





Precision limited to ~50 MeV by theory; scale variations dominant; α_s parametric non-negligible; if not a volunteer for N^4LO calculation refrain from claiming 10 MeV precision

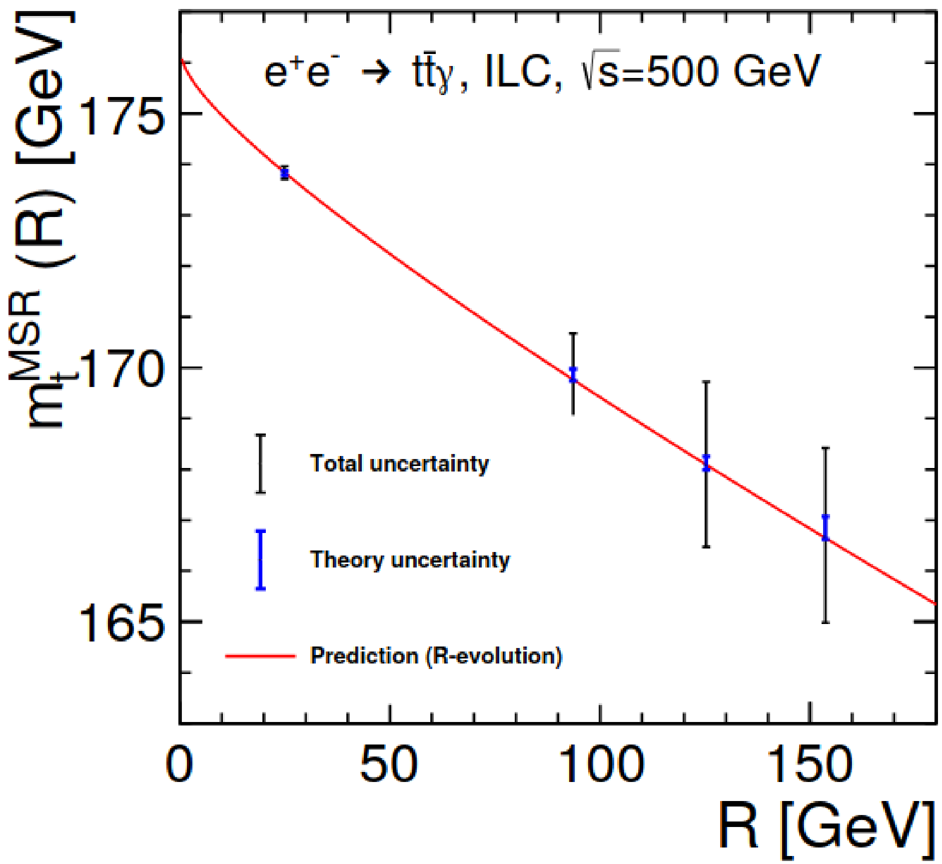
Top quark mass from radiative events



Radiative "return to threshold" in e+e- → ttγ events

Extract short-distance mass with rigorous interpretation and competitive precision:

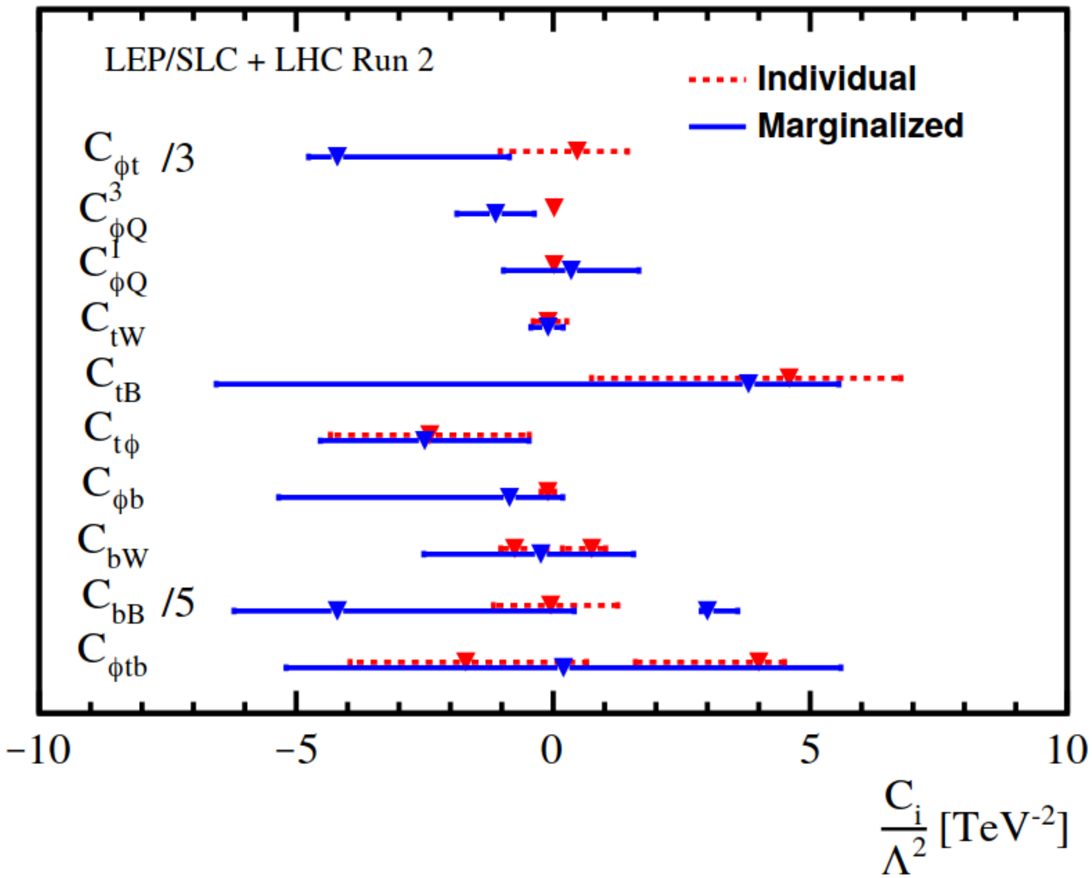
CLIC380 (1/ab): 50 MeV (theory), 110 MeV total
ILC500 (4/ab): 50 MeV (theory), 150 MeV total



5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone

Dedicated fit to top EW operators

Dedicated fit to top and bottom EW operators [M. Perelló et al.]



Current constraints are order(few TeV^{-1})

R^b, A_{FB} @ LEP/SLC

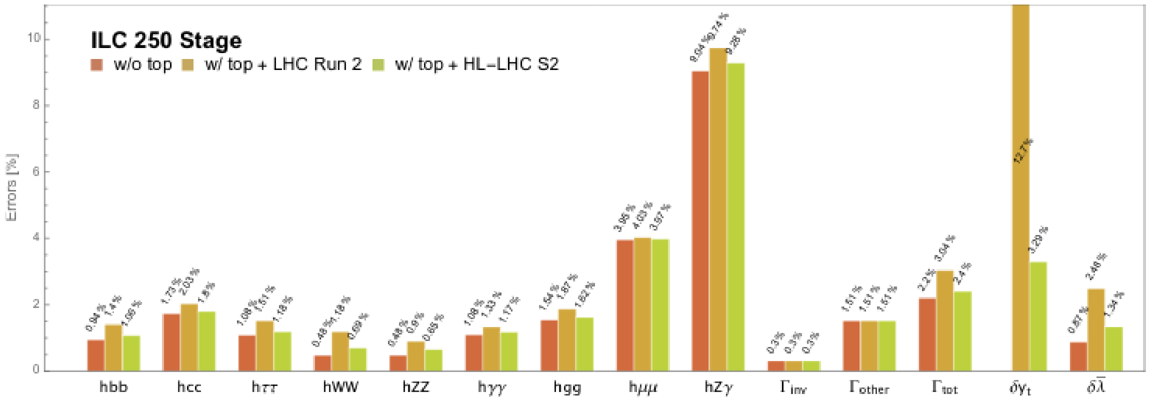
Associated ttX @ LHC

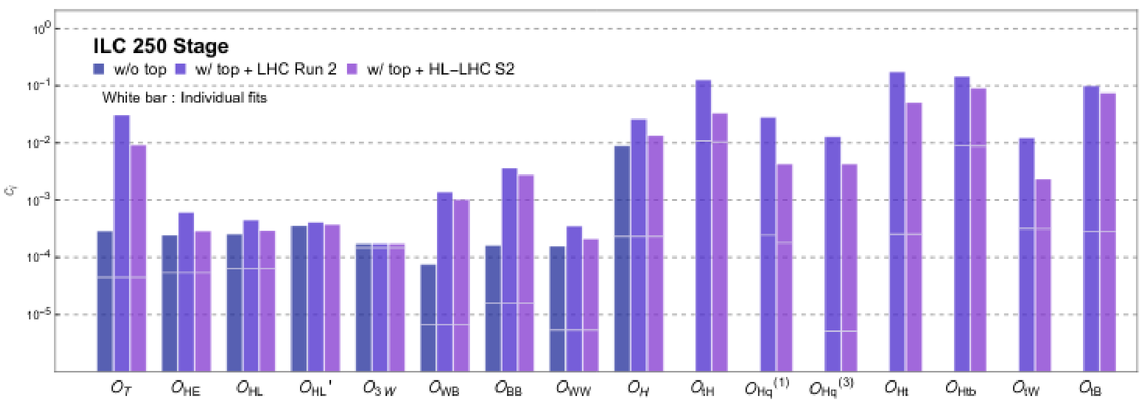
Single top & top decay

→ HepFit implementation with IFIC theory (A. Peñuelas, V. Miralles)

Global top/Higgs/EW fit

Ph.D. Martín Perelló, UV, abr. 2020





Ongoing work: S. Jung, J. Lee, M. Perelló, J. Tian

Threat: “top” degrees of freedom can degrade “Higgs” fit considerably, even with HL-LHC S2 projection

Opportunity: indirect sensitivity to top EW operators (+Yukawa) yields tight single-parameter limits already at 250 GeV

HL-LHC + ILC250 + ILC550 (+ Z-pole) provides very robust bounds on extended Higgs/EW/top operator basis